Astrophysical Constraints on Axion-Photon Coupling

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Outline

- ❑ Stars, particle physics, and Axion bounds from stellar evolutions
- ❑ The Horizontal Brunch bound on the axion-photon coupling
- ❑ Bound on the axion-photon coupling from massive stars
- ❑ Conclusions

Stars as Laboratories

For a particle physicist, stellar interiors represent extremely hermetic detectors, sensitive to very rare processes. For example, the process

$$\gamma \rightarrow \nu + \bar{\nu}$$

E. Braaten, D. Segel
Phys.Rev. D48 (1993)

plays a fundamental role in stellar cooling though the probability of this decay to occur between successive interactions of the plasmon is only ~ 10^{-26}.

The same for

$$e^{+} + e^{-} \rightarrow \nu + \bar{\nu}$$

e.g., D. D. Clayton, “Principles of Stellar Evolution and Nucleosynthesis”, Chicago (1994)

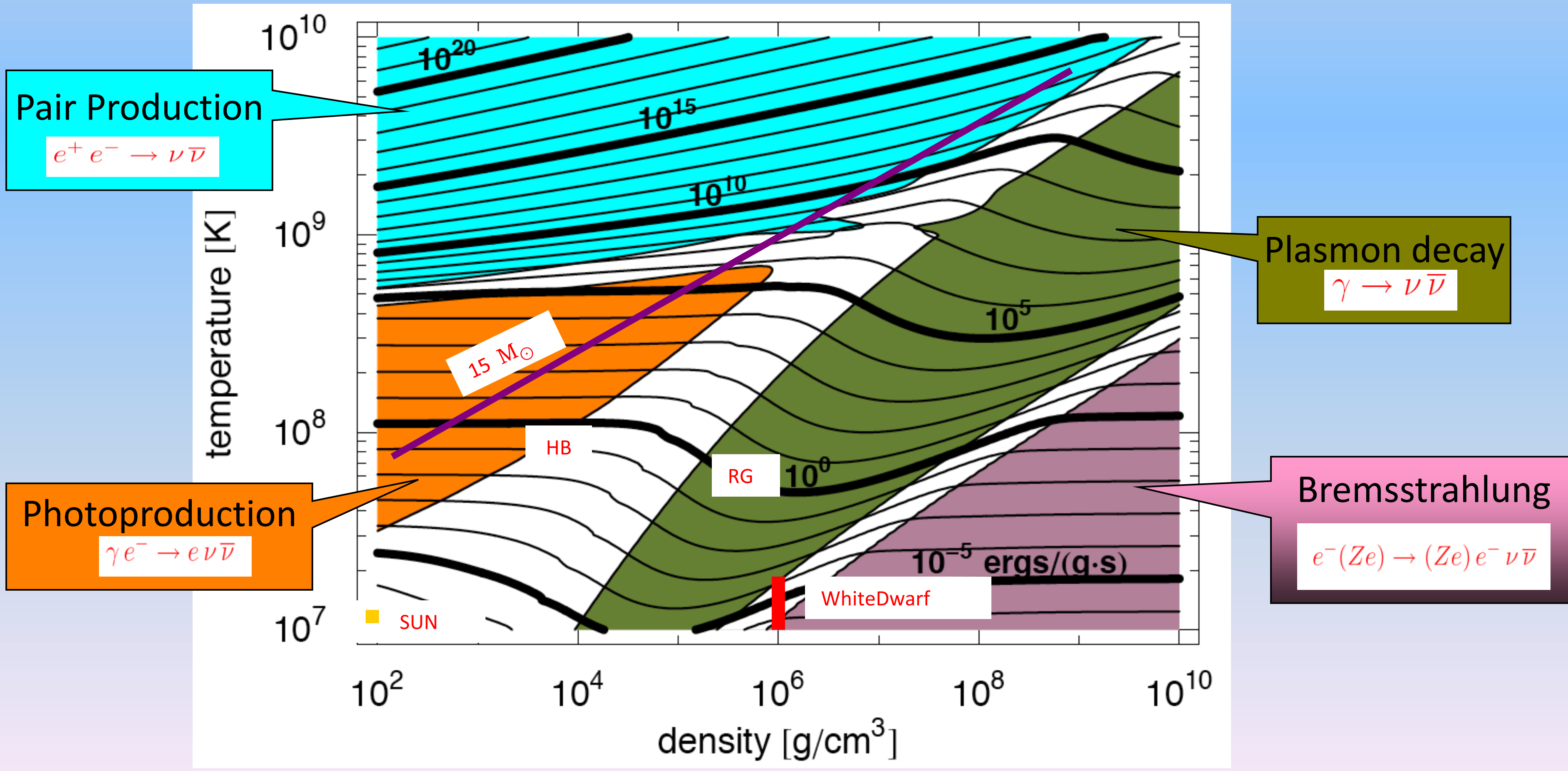
whose branching ratio with respect to the corresponding photon production is 10^{-19}

Stars as Laboratories

Standard Cooling: photons and neutrinos

Photon cooling is relevant in the non-degenerate region, below $T \sim 5 \times 10^8 K$

The labels refer to the star core



Stars as Laboratories

Exactly 50 years ago Bernstain, Ruderman and Feinberg studied the effects of electromagnetic properties of neutrinos for the cooling of the sun. Their bound on the neutrino magnetic moment was better than the experimental bound at that time.

J. Bernstein et al., Phys. Rev. 132, 1227 (1963)

Since then, stars have proven to be excellent laboratories to test physics scenarios with ***light, weakly interacting* particles**. Examples include <u>majorons</u>, <u>extra-dimensional photons</u>, <u>novel baryonic or leptonic forces</u>, <u>unparticles</u>, etc.

H.M. Georgi, S.L. Glashow, and S. Nussinov, Nucl. Phys. B193, 297 (1981)

A. Friedland and M. Giannotti, Phys. Rev. Lett. 100, 031602 (2008)

Grifols and E. Masso, Phys. Lett. B 173, 237 (1986)

S. Hannestad, G. Raffelt, and Y.Y.Y. Wong, Phys. Rev. D76, 121701 (2007)

The Axion

A particularly interesting example of light, weakly interacting particle is the **axion**, hypothetical particle whose existence is a prediction of the Peccei-Quinn solution of the Strong CP problem.

Peccei and Quinn (1977),
Weinberg (1978),
Wilczek (1978)

In addition, the axion is a prominent dark matter candidate.

Preskill, Wise and Wilczek (1983)
Abbott and Sikivie (1983)
Dine and Fischler (1983)
Turner (1986)

Axions interact with matter and radiation. In the *standard* (QCD) *axion models* the axion interaction with matter and photons and the axion mass are related through the phenomenological Peccei-Quinn constant f_a

$$L_{\text{int}} = -i\frac{C_i m_i}{f_a} a\overline{\psi}\gamma_5\psi - \frac{1}{4} g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Axion-photon coupling

$$m_a \approx \frac{6\,\text{eV}}{f_a/10^6\,\text{GeV}}$$

$$g_{a\gamma} = \xi \frac{\alpha_{em}}{2\pi\ f_a}$$

Axion-Like Particles (ALPs)

In the standard axion models the axion interactions and mass are related in terms of the Peccei-Quinn constant f_{a}.

However, recently there has been an effort to study more general models where the coupling constants and the mass are unrelated (**ALPs**).

In the case of ALPs, the different coupling are unrelated.

$$\boxed{L_{\mathrm{int}} = -g_{ai}\frac{\partial_\mu a}{2m_i}\bar{\psi}_i\gamma_5\gamma_\mu\psi_i - \frac{g_{a\gamma}}{4}a\,F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

A. Ringwald,
Phys.Dark Univ. 1 (2012)

D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D.Montanino, M. Roncadelli, Phys. Rev. D 86, 075024 (2012)

J. Jaeckel and A. Ringwald, Ann. Rev. Nucl.Part.Sci. 60,405 (2010)

I. Irastorza, F. Avignone, S. Caspi, J. Carmona, T. Dafni, et al.,
JCAP 1106, 013 (2011)

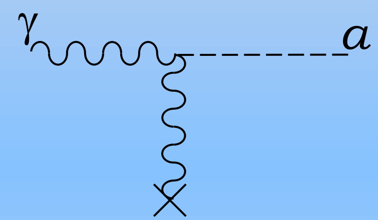
D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D. Montanino, et al.,
Phys.Rev. D86, 075024 (2012)

Axions and Stellar Evolution

Light axions can be produced in stars through various mechanisms, e.g.

Primakoff conversion

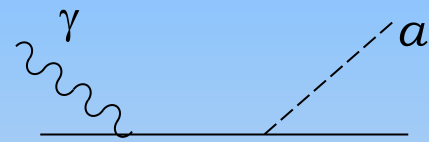
$$\gamma + Ze \rightarrow a + Ze$$



Relevant in He-burning stars

Compton scattering

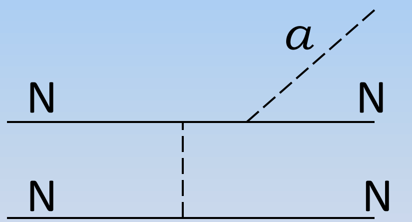
$$\gamma + e \rightarrow a + e$$



Relevant in RG and WD

Nucleon Bremsstrahlung

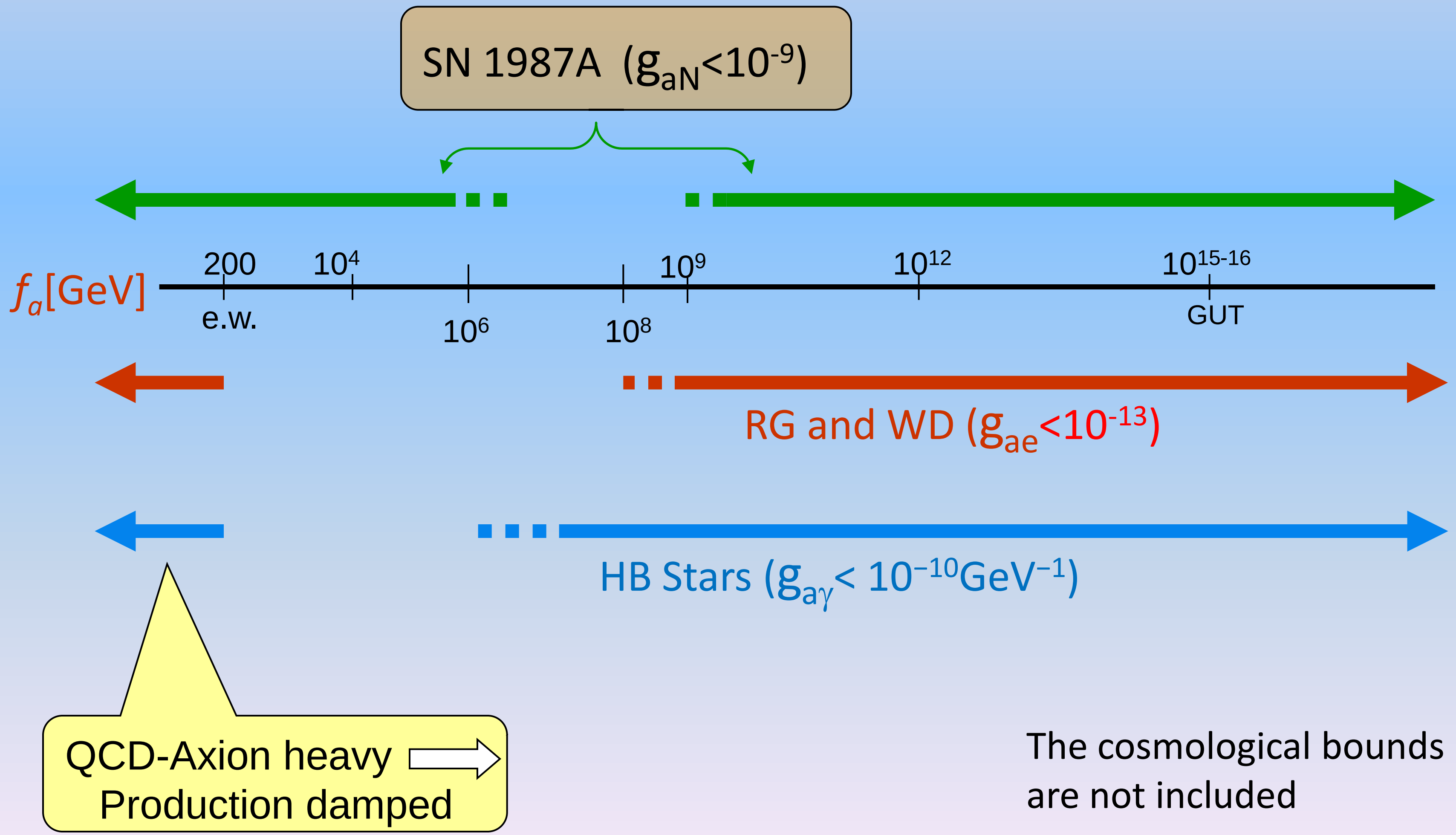
$$N + N \rightarrow N + N + a$$



Relevant in SN and neutron stars

The emission of axions could lead to an *overly efficient energy drain*, inconsistent with observations. This leads to bounds on the axion couplings with photons, electrons and nuclei.

Summary of the stellar bounds (QCD-Axion)



The cosmological bounds are not included

Axion detection: the role of the Axion-Photon Coupling

Most of the modern axion searches are based on the microwave cavity detection proposed by P. Sikivie, which relays on the axion-photon coupling. Axions can be converted into photons in an external magnetic filed. These bounds depend on the axion mass.

P. Sikivie, Phys.Rev.Lett. 51, 1415 (1983)

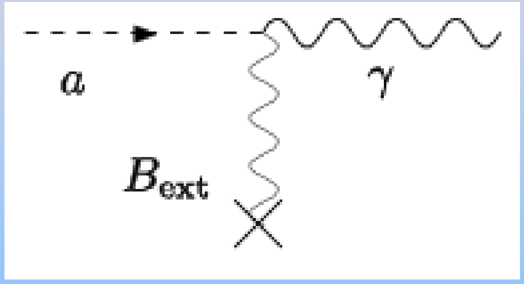
The current best terrestrial bound on the axion (ALPs)-photon coupling is the one from the Cern Axion Solar Telescope (**CAST**)

$$\boxed{g_{a\gamma} \leq 0.88 \times 10^{-10}\,\mathrm{GeV}^{-1}}$$

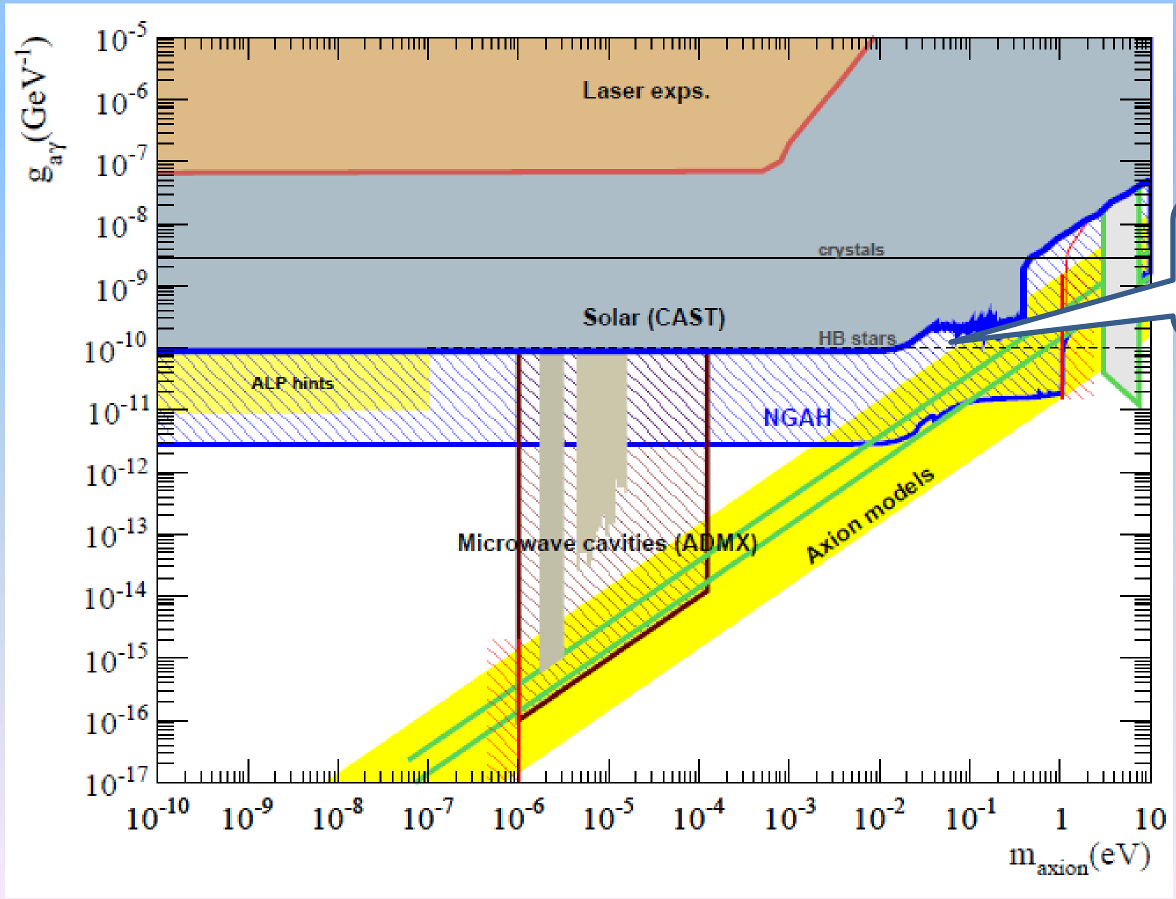
The bound is however weakened at masses in the QCD –axion region

Experimental Axion (and ALPs) Search

Among the major axion experiments is the <u>Cern Axion Solar Telescope (</u>**CAST**), which is looking for axions from the sun. The Next Generation Axion Helioscopes (NGAH) are expected to improve the bounds by over an order of magnitude.



Axion-photon vertex

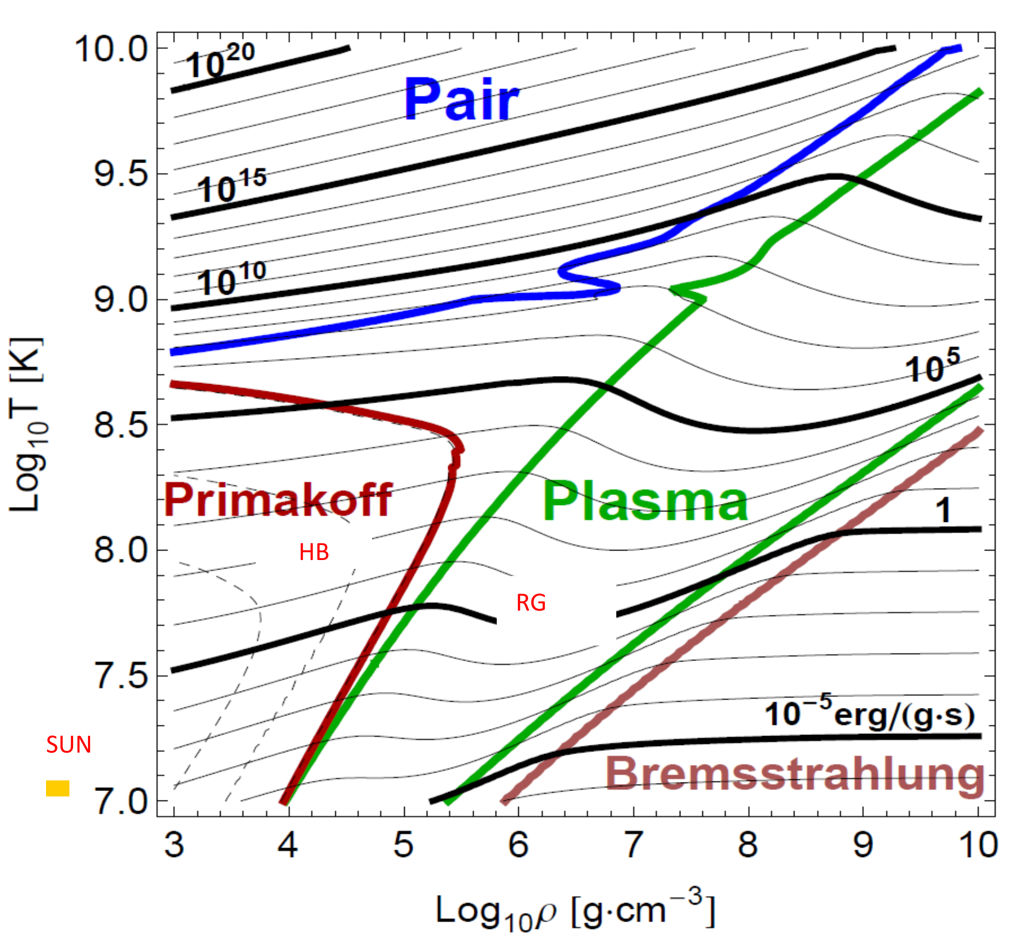


HB-bound, g_{10}=1.
Raffelt and Dearborn (1987)

from I. G. Irastorza et al., *Latest results and prospects of the CERN Axion Solar Telescope*, Journal of Physics: Conference Series **309 (2011) 012001**

Primakoff production of Axions in Stars

Axions can be produced in the core of a star through Primakoff photon conversion, γ +(Ze) → a +(Ze), in the field of a nucleus.

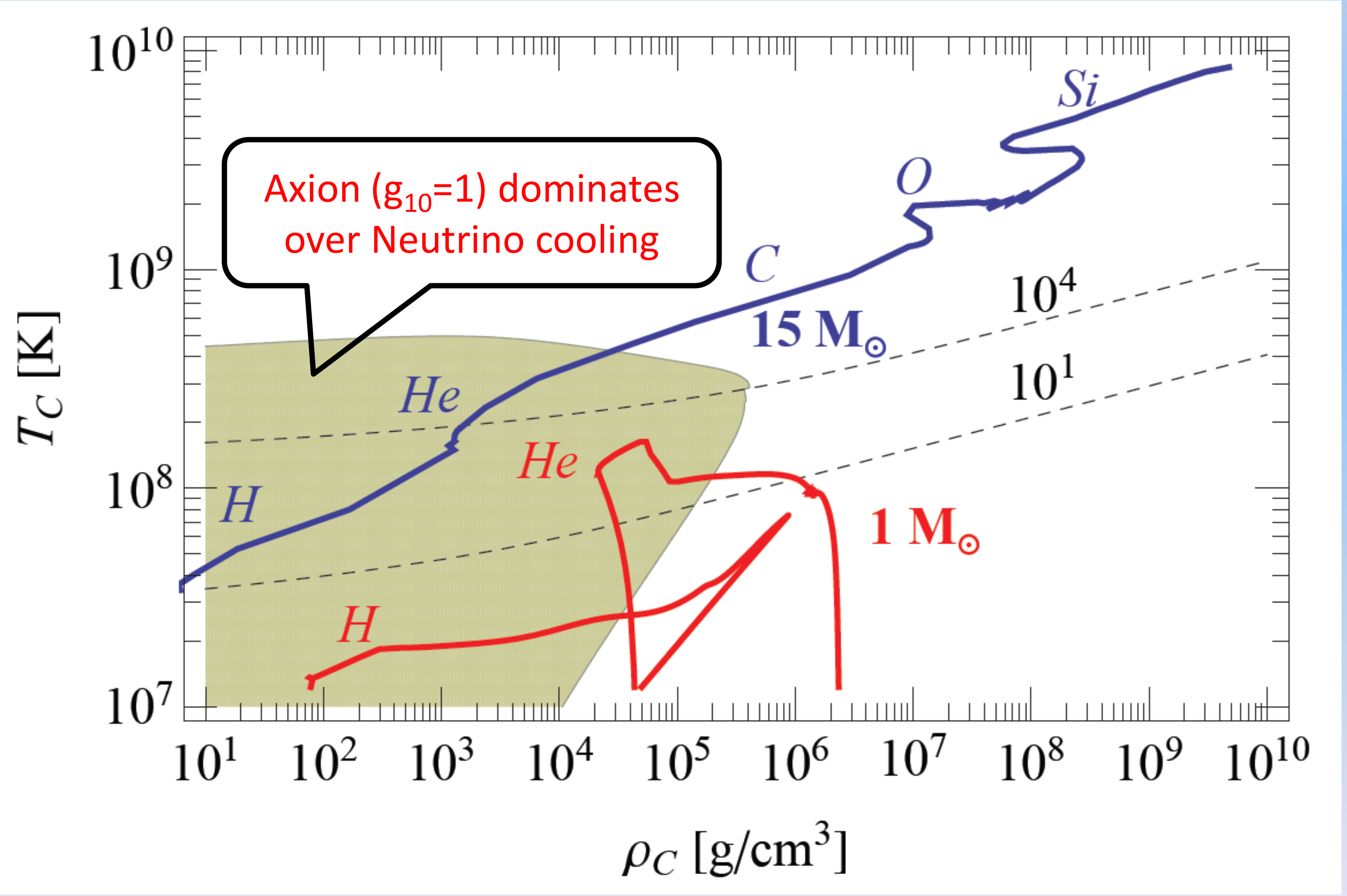


The axion energy loss is very sensitive to the temperature.

HB stars are, evidently, in the region where axion dominates over neutrino cooling

The HB bound on the axion-photon Coupling

Axions can be produced in the core of a star from photons interacting with the electric field of the nuclei (**Primakoff process**).



Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

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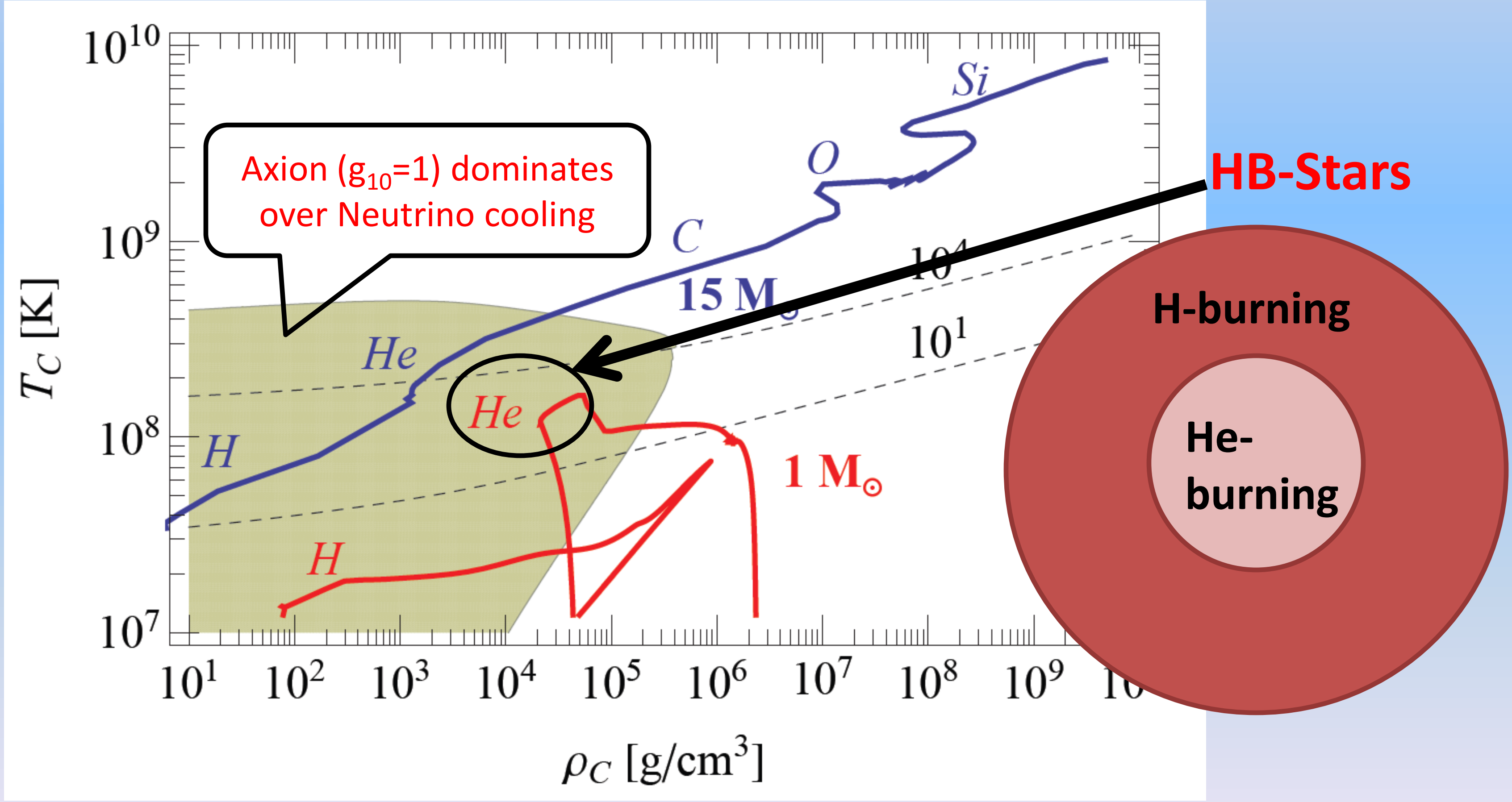
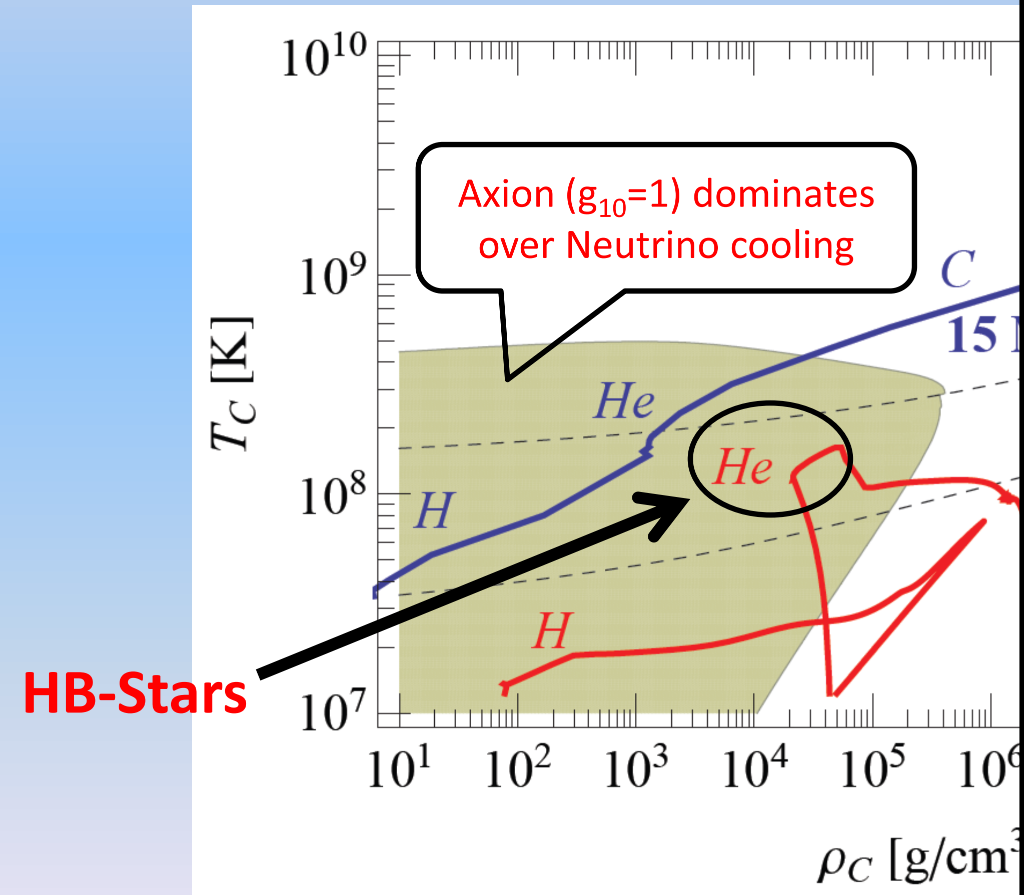


Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

The HB bound on the axion-photon Coupling

Axions can be produced in the core of a
interacting with the electric field of the



Friedland, Giannotti, Wise, **Phys. Rev.**

Axions coupled too strongly to photons would <u>speed up the consumption of He in the HB star core and reduce the HB lifetime</u>.

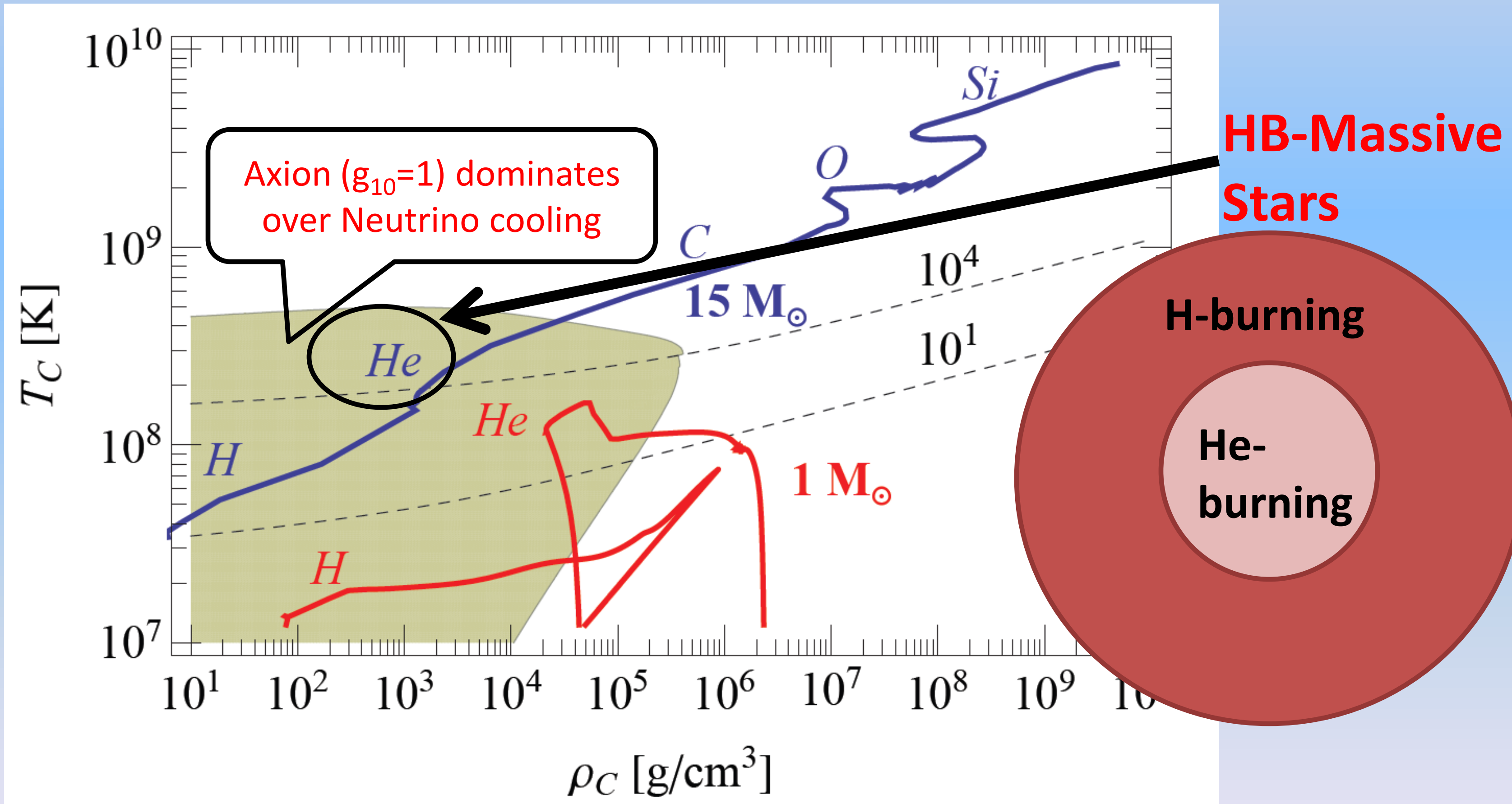
Observational constrains come from the <u>comparison of the number of HB vs. RG stars</u>.

The bound $g_{a\gamma} \leq 10^{-10}\text{GeV}^{-1}$ [G.G. Raffelt and D.S.P. Dearborn, **Phys. Rev. D36, 2211(1987)**] (which is the one currently reported in the PDG) corresponds to a <u>reduction of the HB star lifetime by 30%</u>.

The bound applies to axion masses <30 keV or so.

Axion and He-burning massive stars

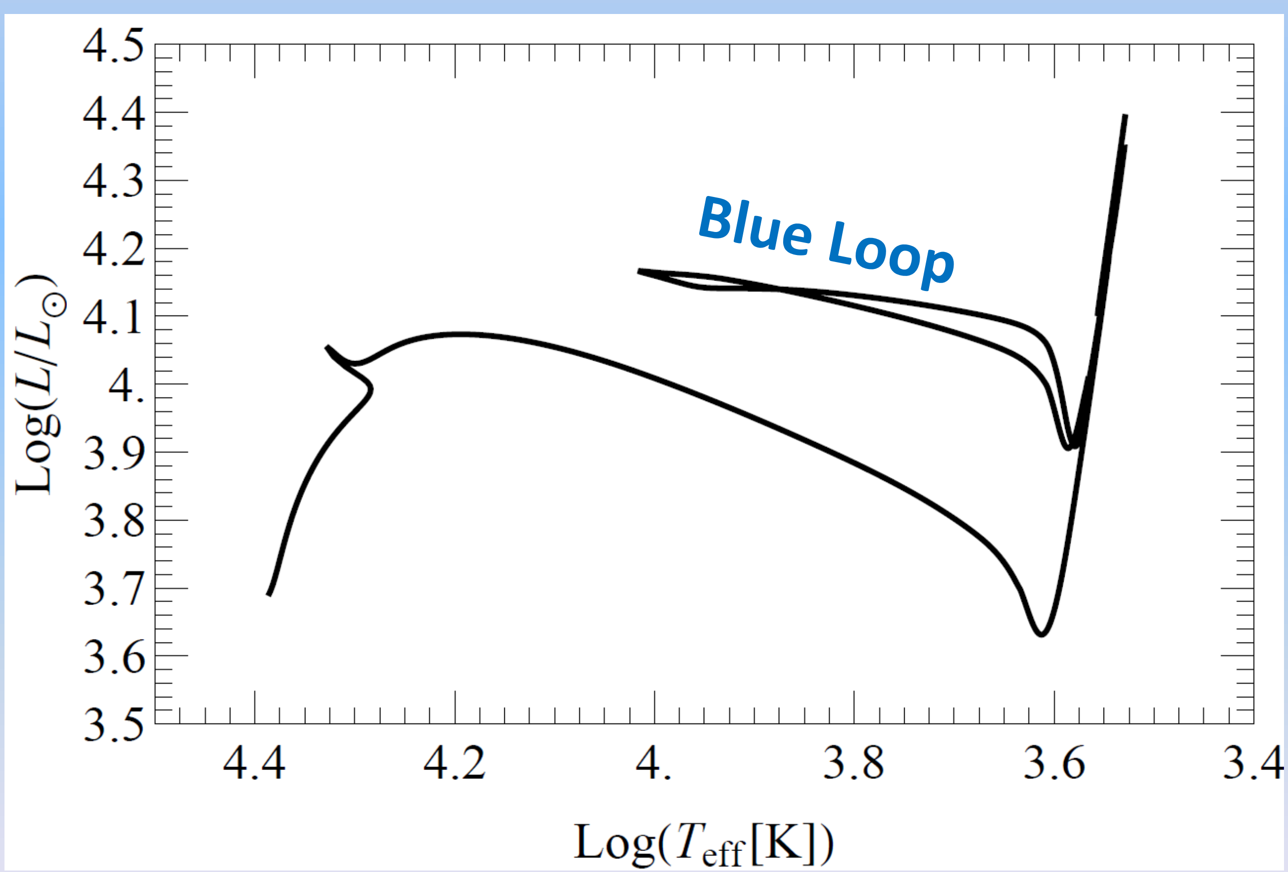
However, it is massive stars that provide the currently strongest bound on the axion-photon coupling



Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

The Blue Loop

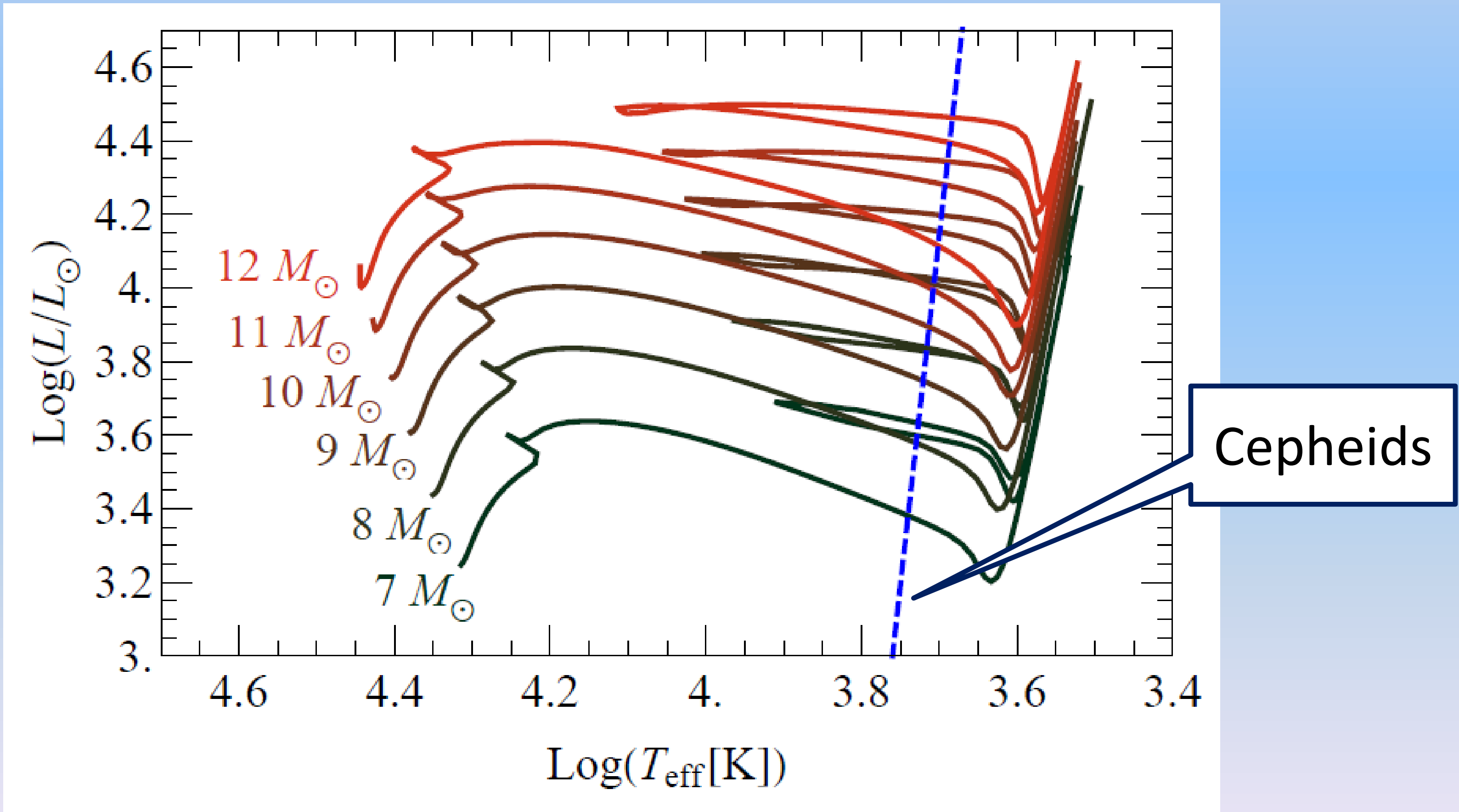
The HR diagram shows the luminosity v.s. surface temperature of a star.
The **blue loop** is a prominent feature of the evolution of a massive star.



Simulations for a $9.5\mathrm{M}_\odot$, solar metallicity, from main sequence to end of He-burning.
MESA (Modules for Experiments in Stellar Astrophysics), Paxton et al. *ApJ Suppl*. **192** 3 (2011) [arXiv:1009.1622]

The Blue Loop and the Cepheids

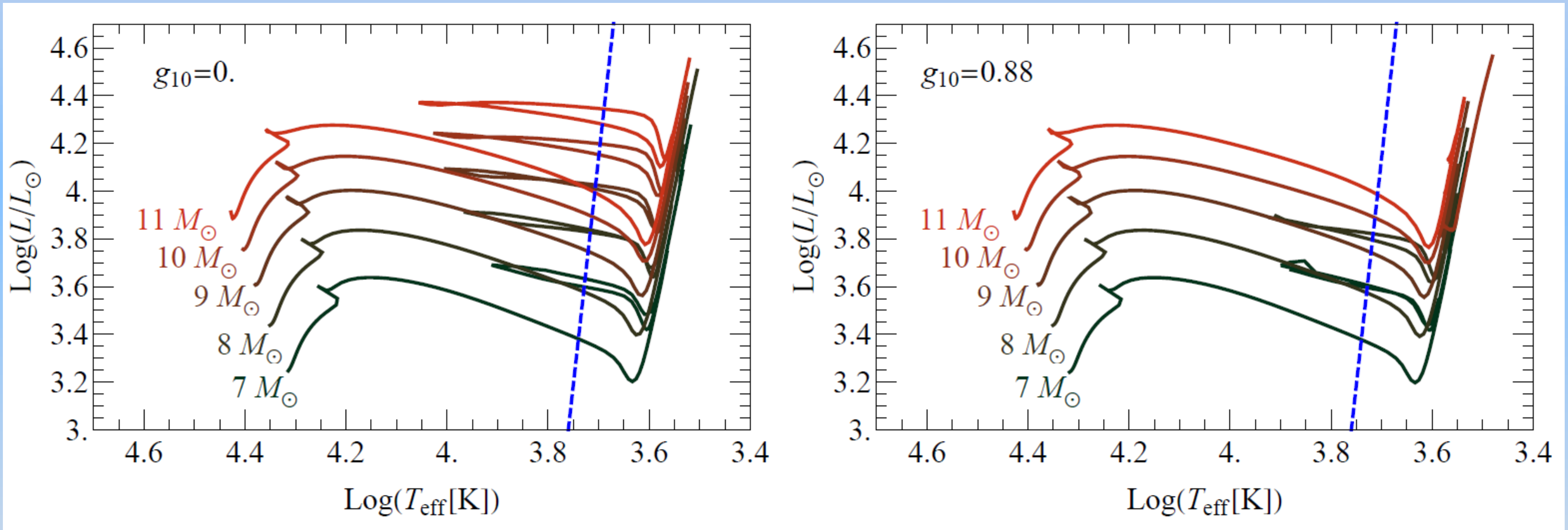
The blue loops are necessary to explain the existence of the Cepheids



Simulations of evolution in H-R diagram of stars with solar metallicity, from main sequence to end of He-burning. **[MESA]**

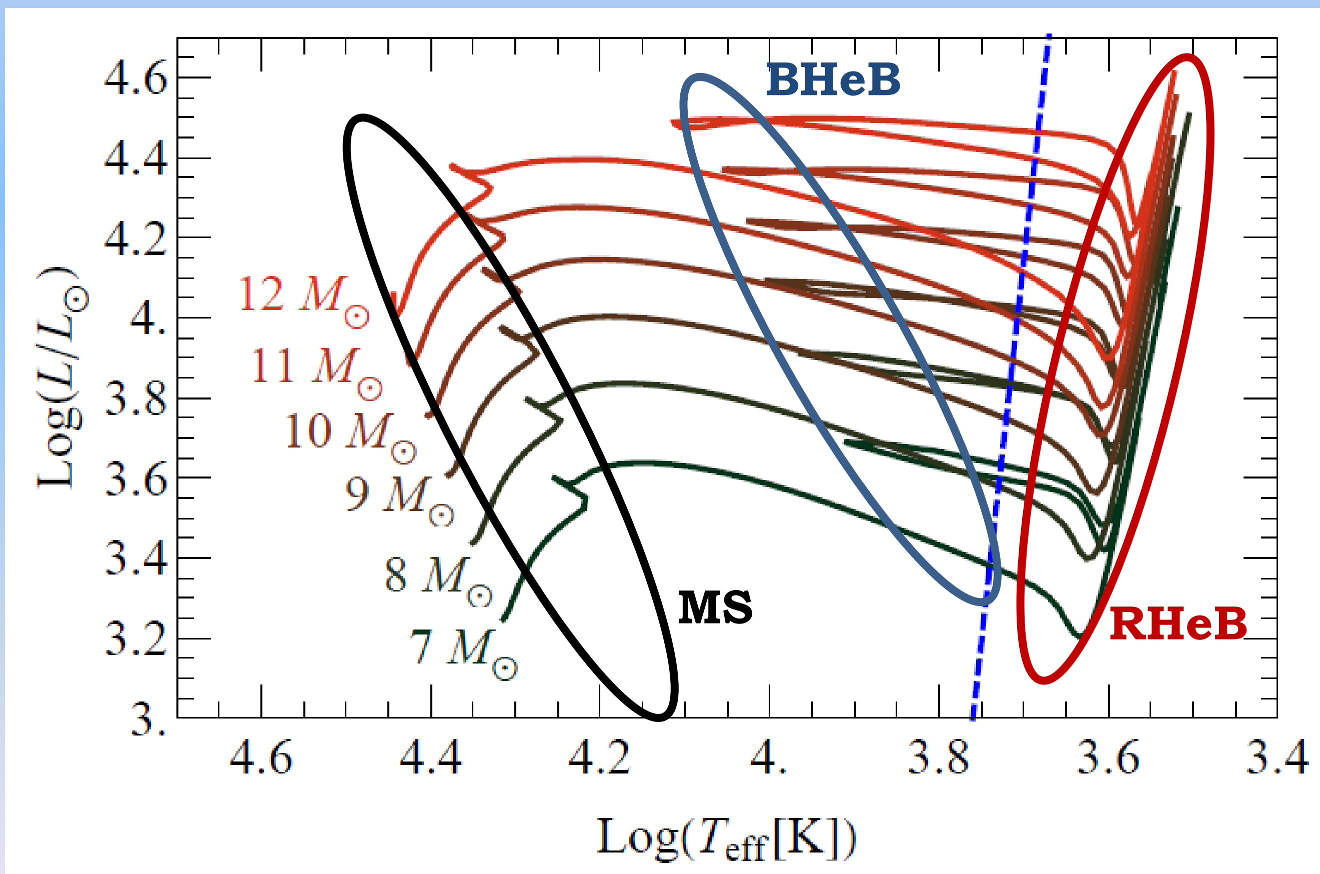
Axions effects on the Blue Loop

The value g_{10}=0.88 corresponds to the current CAST bound on the axion-photon coupling.



A value of g_{10}=0.8 would provide qualitative changes in the stellar evolution. In particular, it would eliminate the blue loop stage of the evolution, leaving one without an explanation for the existence of Cepheid stars in a broad range of pulsation periods.

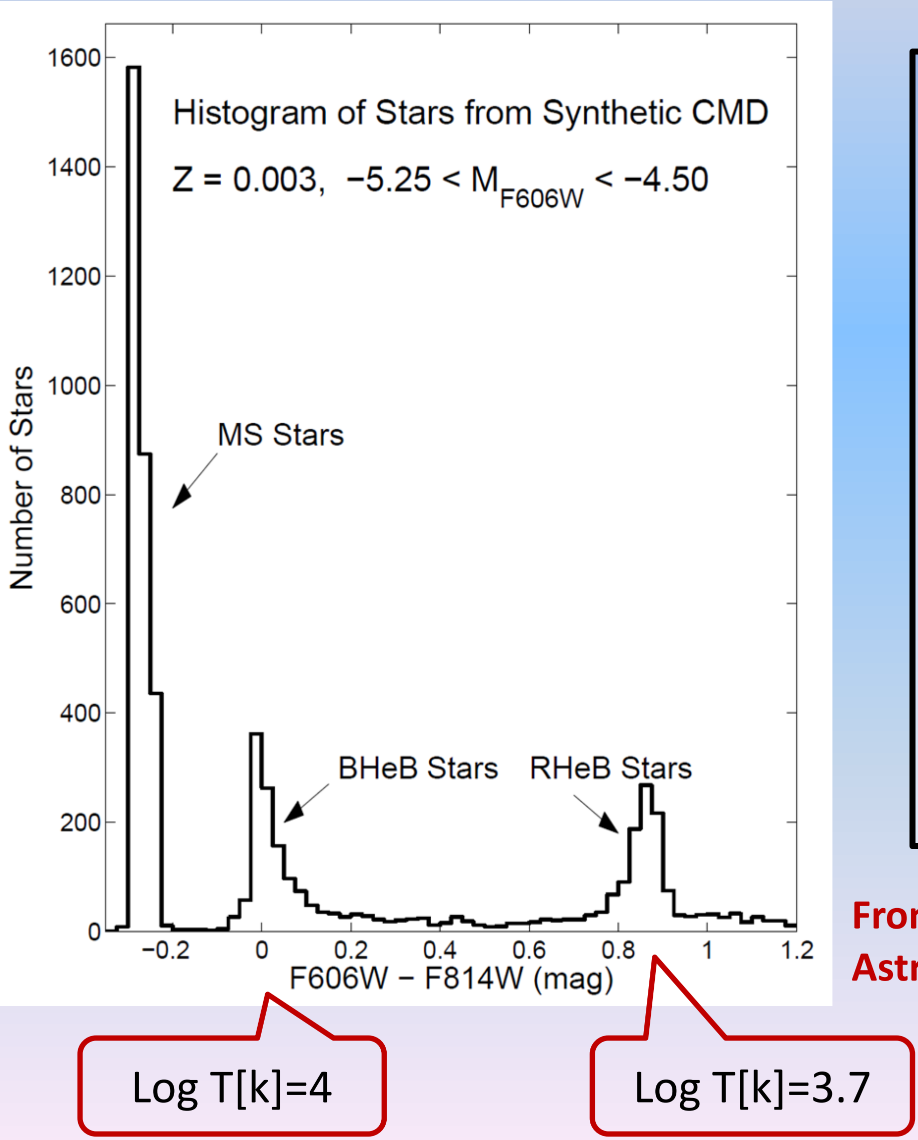
Observations of massive stars: Main, Blue and Red Sequences



Most of the star life-time is spent in one of the three sequences: the **Main Sequence** (central H-burning), the **Red** central **He-Burning** sequence, and the **Blue** central **He-Burning** sequence

Simulations of evolution in H-R diagram of stars with solar metallicity, from main sequence to end of He-burning. **[MESA]**

Observable evolutionary Phases: Central H- and He-burning



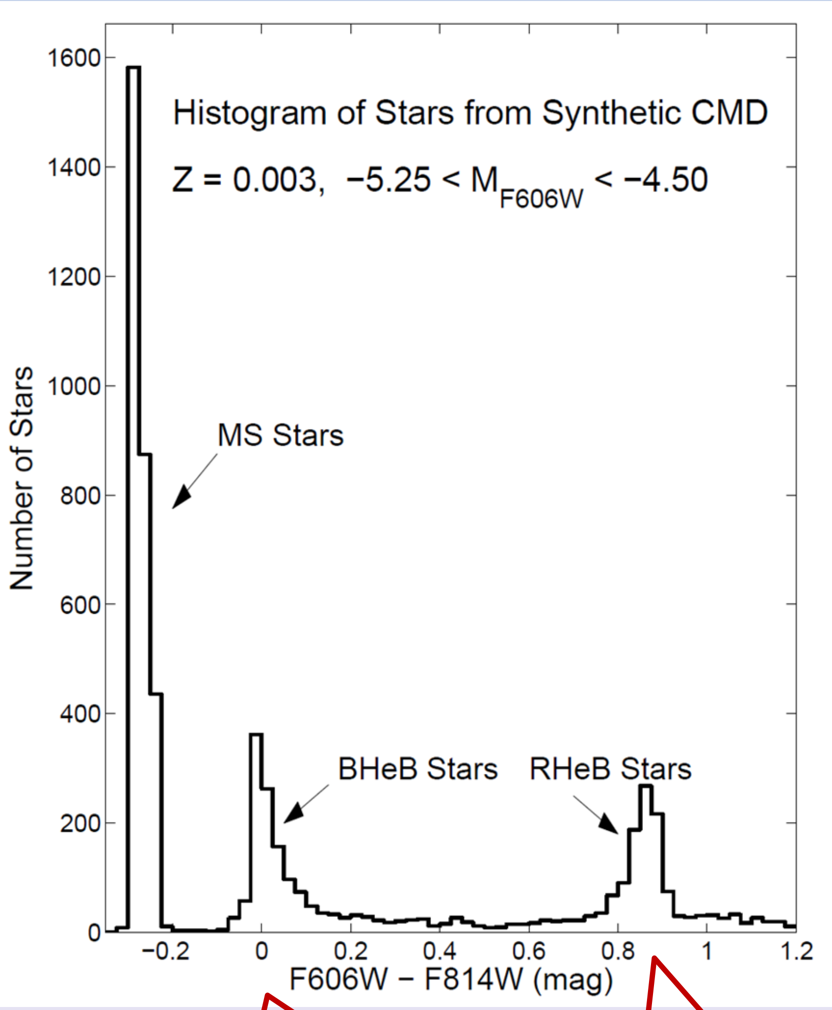
Blue stars have been observed for many decades and measurements are very accurate.

The contamination from MS stars transitioning to BHeB is conservatively estimated to be less than 10% (Dohm-Palmer & Skillman 2002).

The complete disappearance of all blue stars in certain luminosity regions is physically unacceptable.

From Kristen B. W. McQuinn et. al., Astrophys.J. 740 (2011)

Observable evolutionary Phases: Central H- and He-burning



Log T[k]=4

Log T[k]=3.7

Result:

A value of g_{10} above 0.8 would be incompatible with the current observations of HeB sequences.

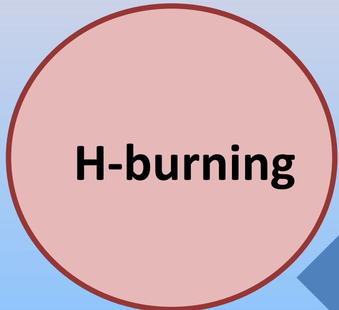
This analysis provides the strongest bound to date on the axion-photon coupling.

A.Friedland, M.G., and M.Wise,
Phys. Rev. Lett. 110, 061101 (2013)

See also
G. Raffelt, http://physics.aps.org/articles/v6/14

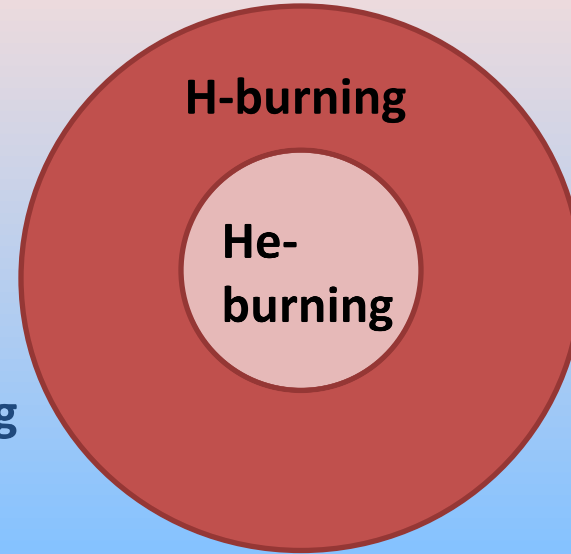
Astrophys.J. 740 (2011)

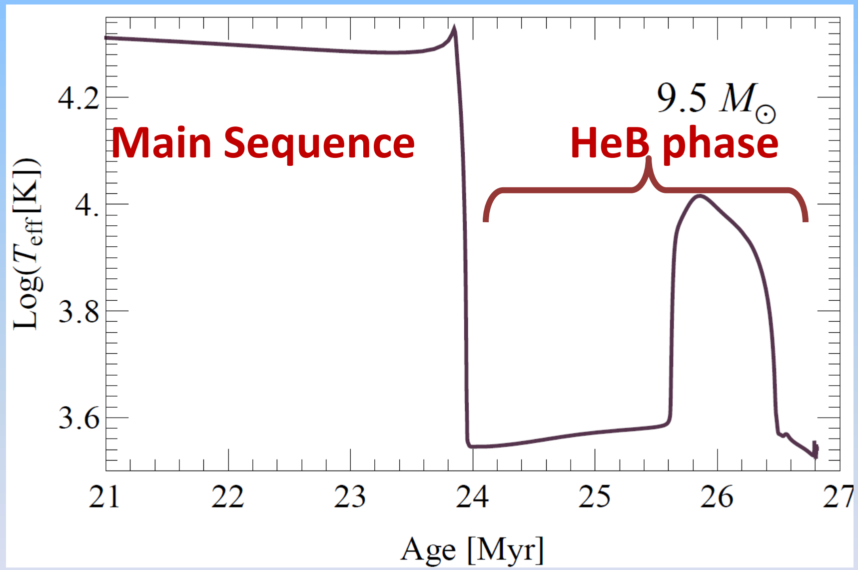
Massive stars and the Blue Loop

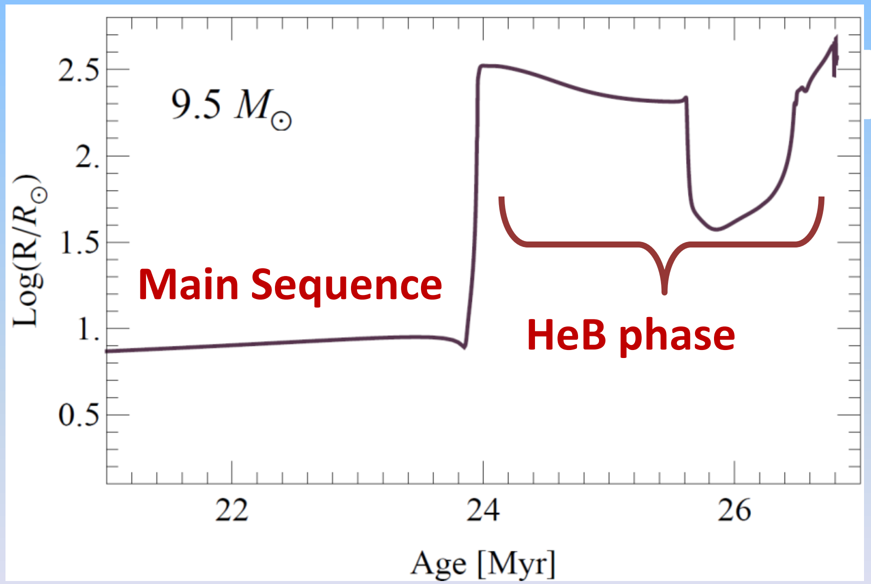


H-burning phase (Main Sequence)

He-burning phase





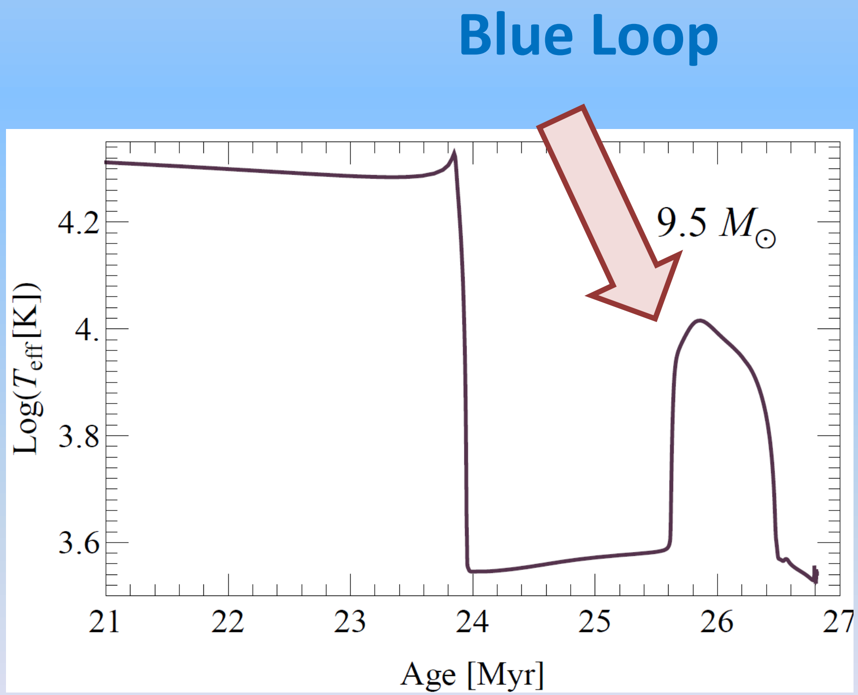


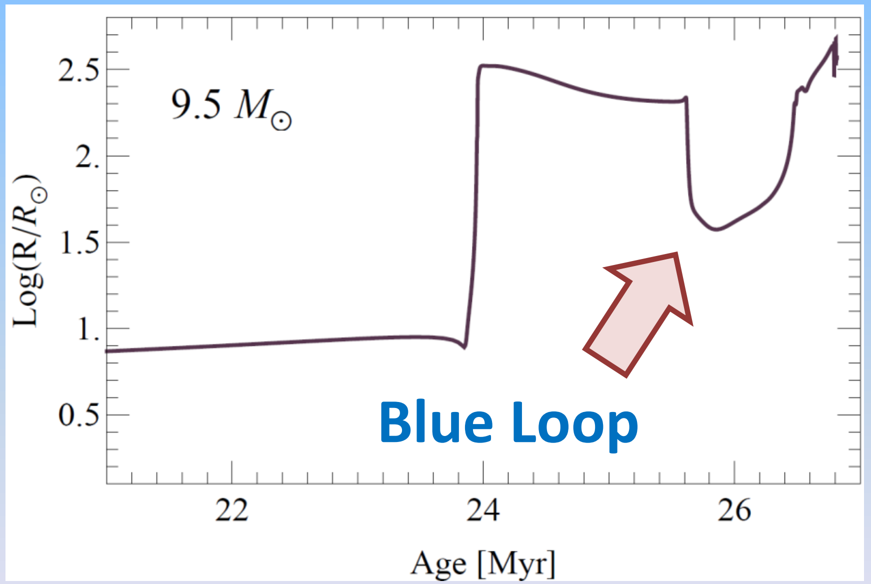
Simulations for a 9.5$M_\odot$, solar metallicity, from main sequence to end of He-burning.

MESA (Modules for Experiments in Stellar Astrophysics), Paxton et al. *ApJ Suppl*. **192** 3 (2011) [arXiv:1009.1622]

The Blue Loop

The journey of the star toward the hotter regions and back is called the **blue loop**. It happens for stars of a few solar masses during the He-burning stage.





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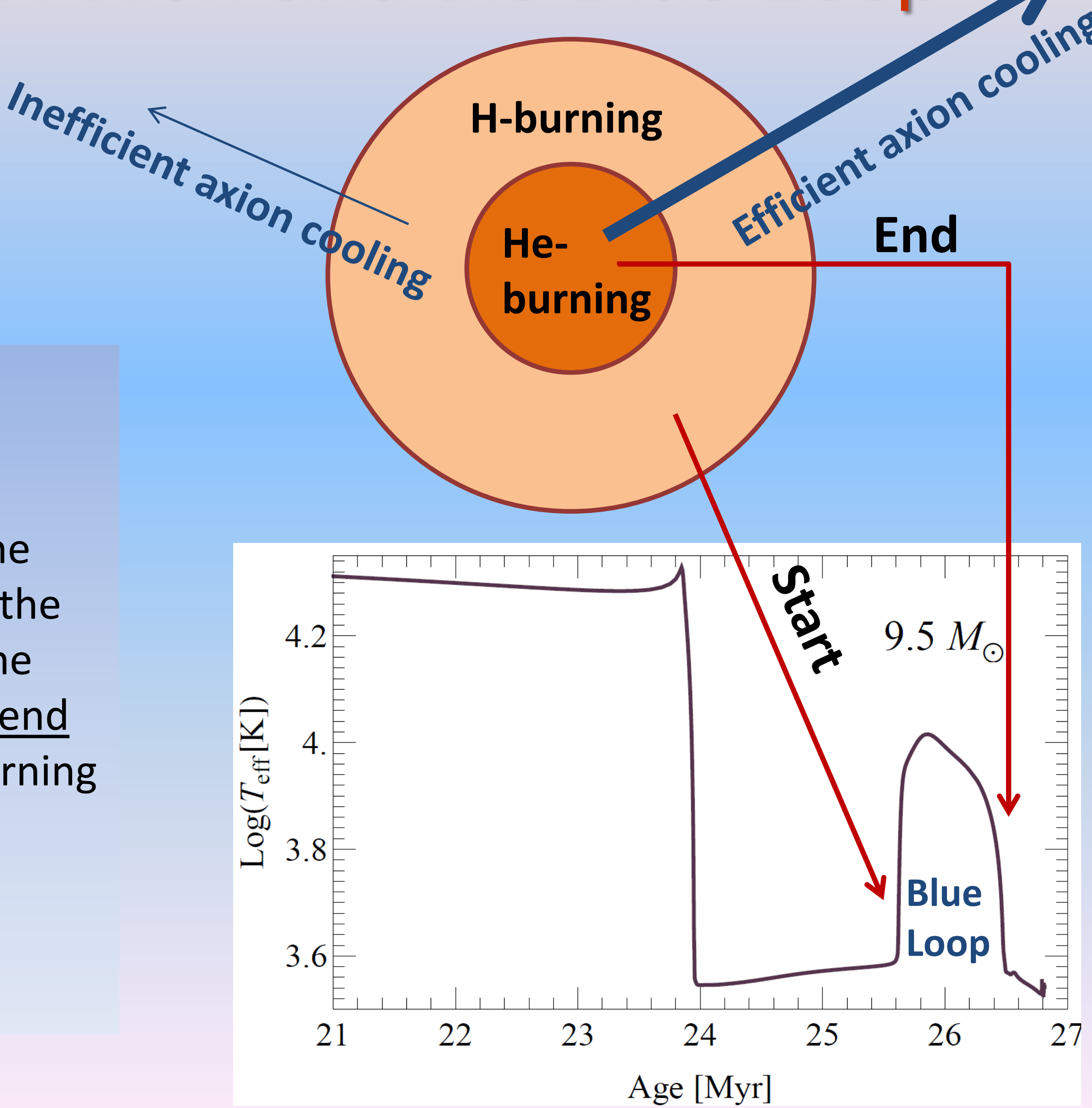
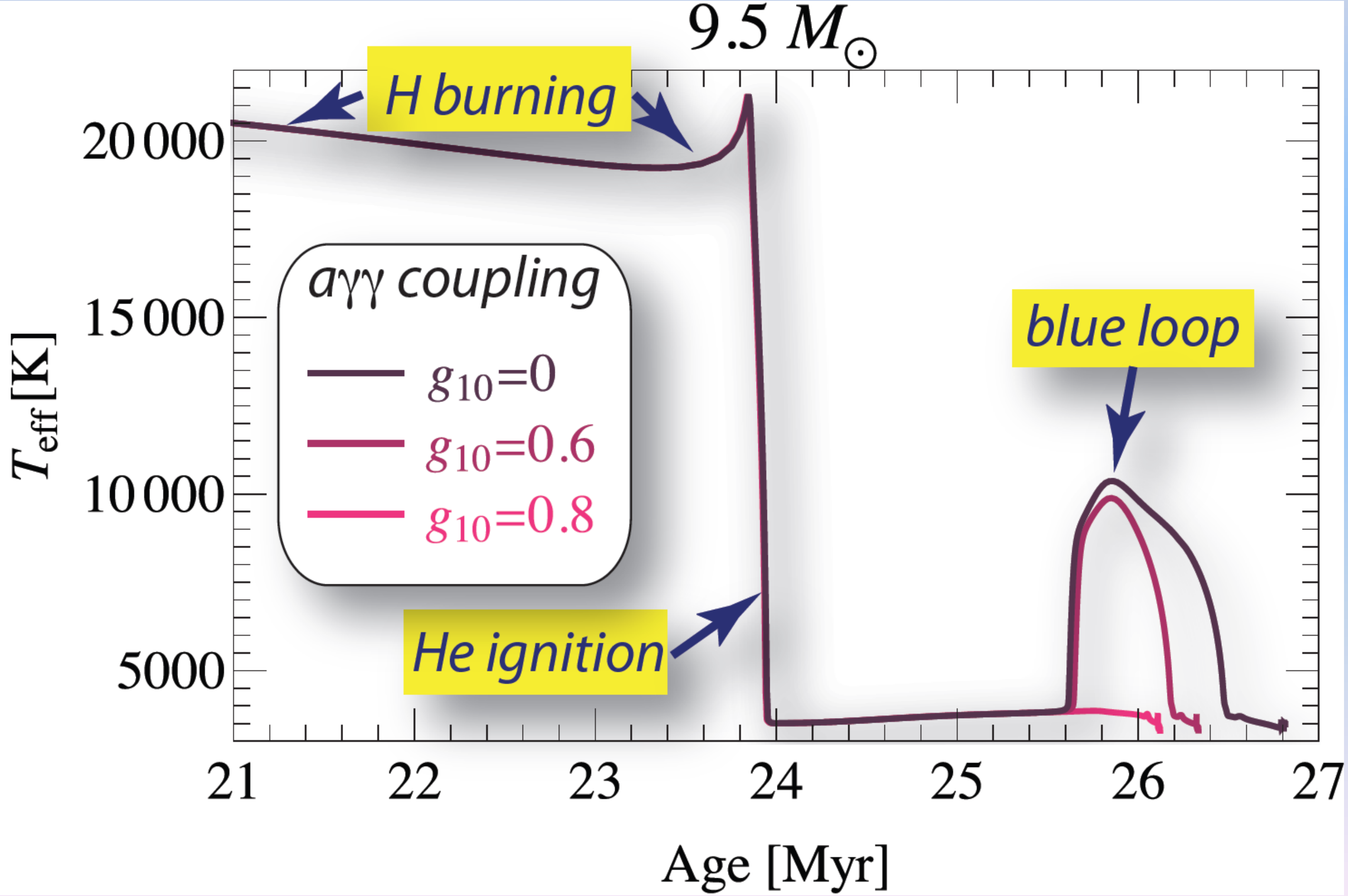
The Axion and the Blue Loop

Blue Loop:

the <u>beginning</u> of the blue loop is set by the H-burning shell time scale whereas the <u>end</u> is set by the He-burning core time scale [Kippenhahn and Weigert (1994)]

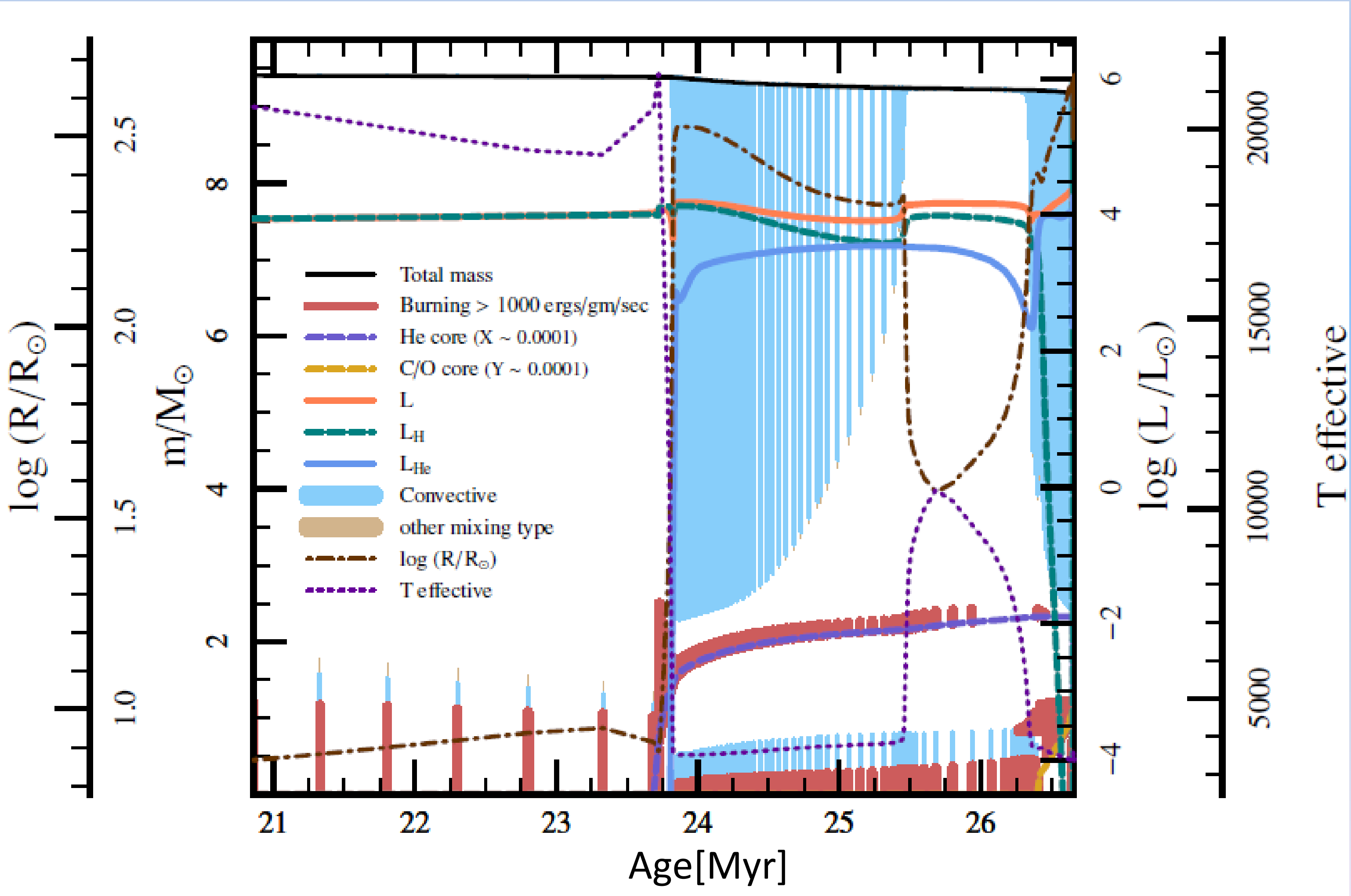


The Axion and the Blue Loop



Axions effects on the Blue Loop

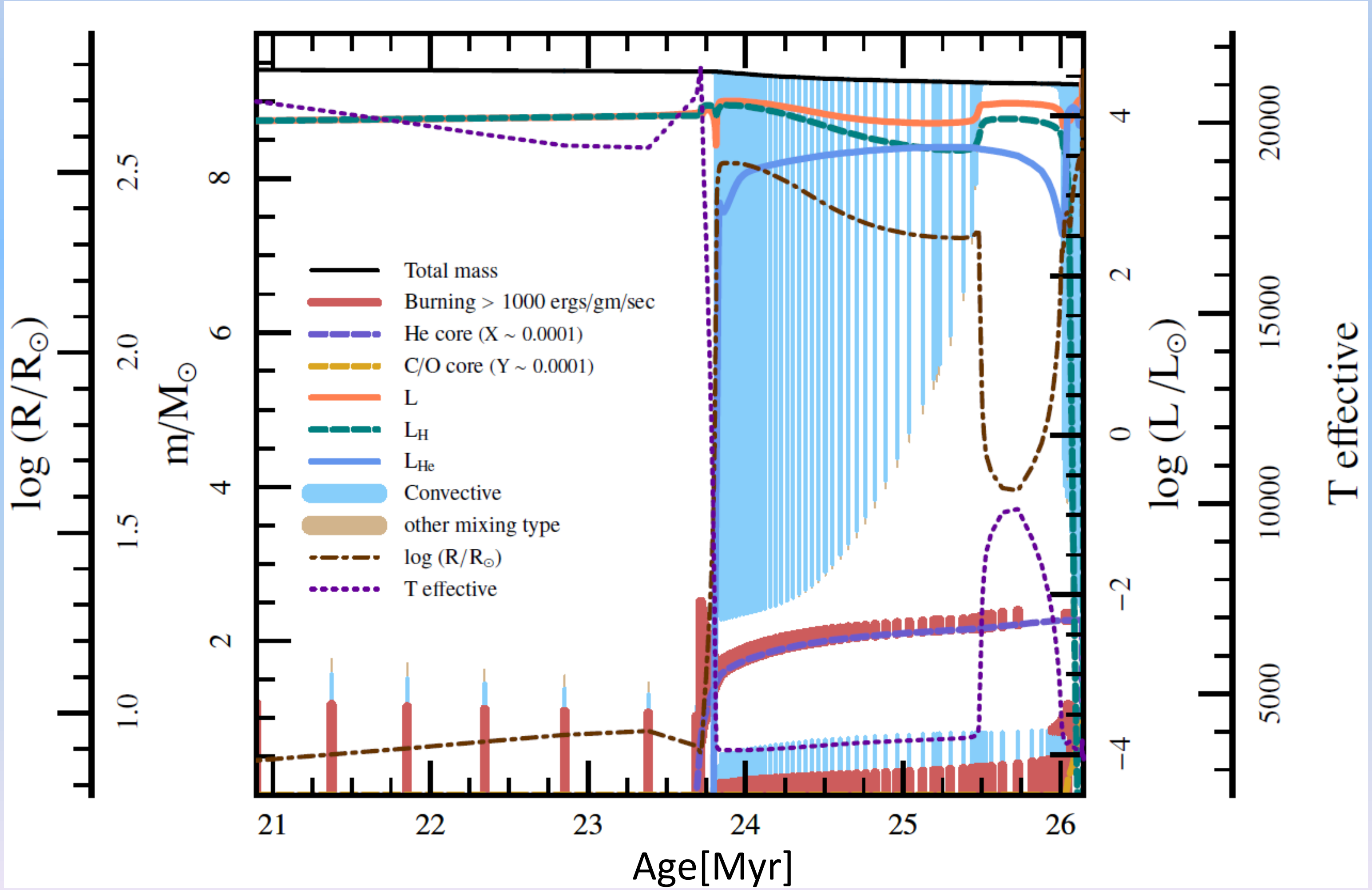
9.5 $M_\odot$ star, g_{10}=0 (No Axion)



MESA Simulation. Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

Axions effects on the Blue Loop

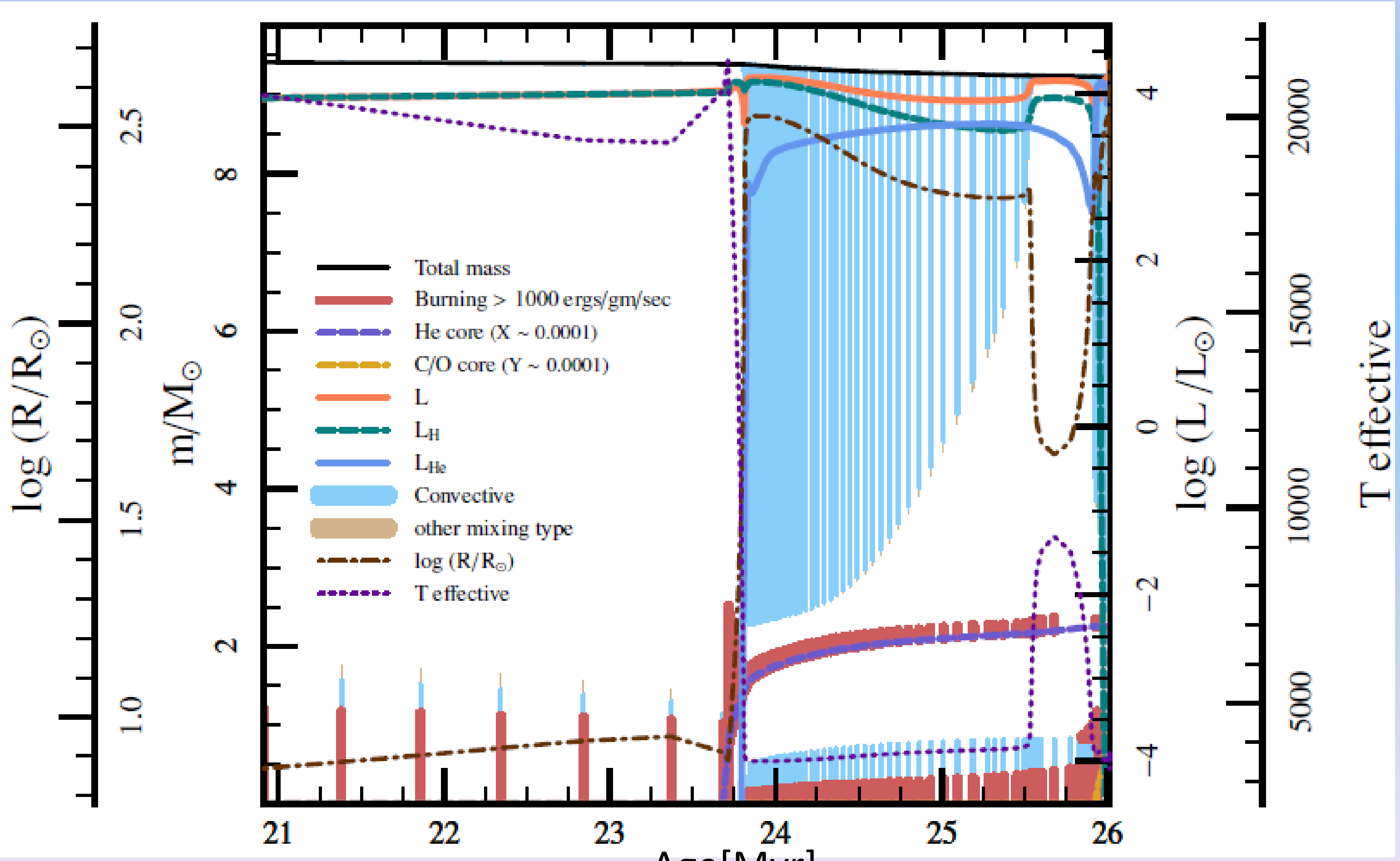
9.5 $M_\odot$ star, g_{10}=0.6



MESA Simulation. Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

Axions effects on the Blue Loop

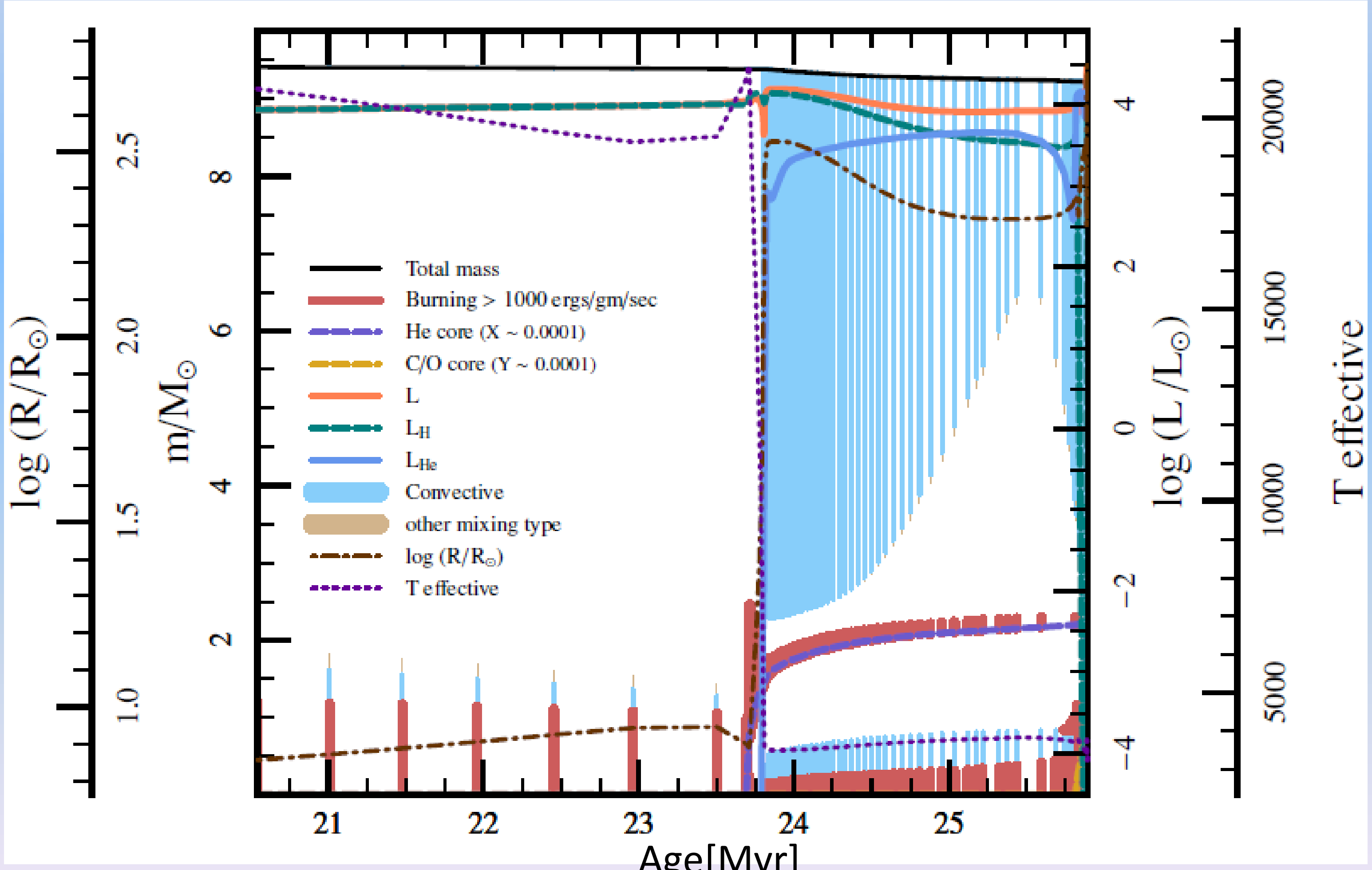
9.5 $M_\odot$ star, g_{10}=0.7



MESA Simulation. Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

Axions effects on the Blue Loop

9.5 $M_\odot$ star, g_{10}=0.8

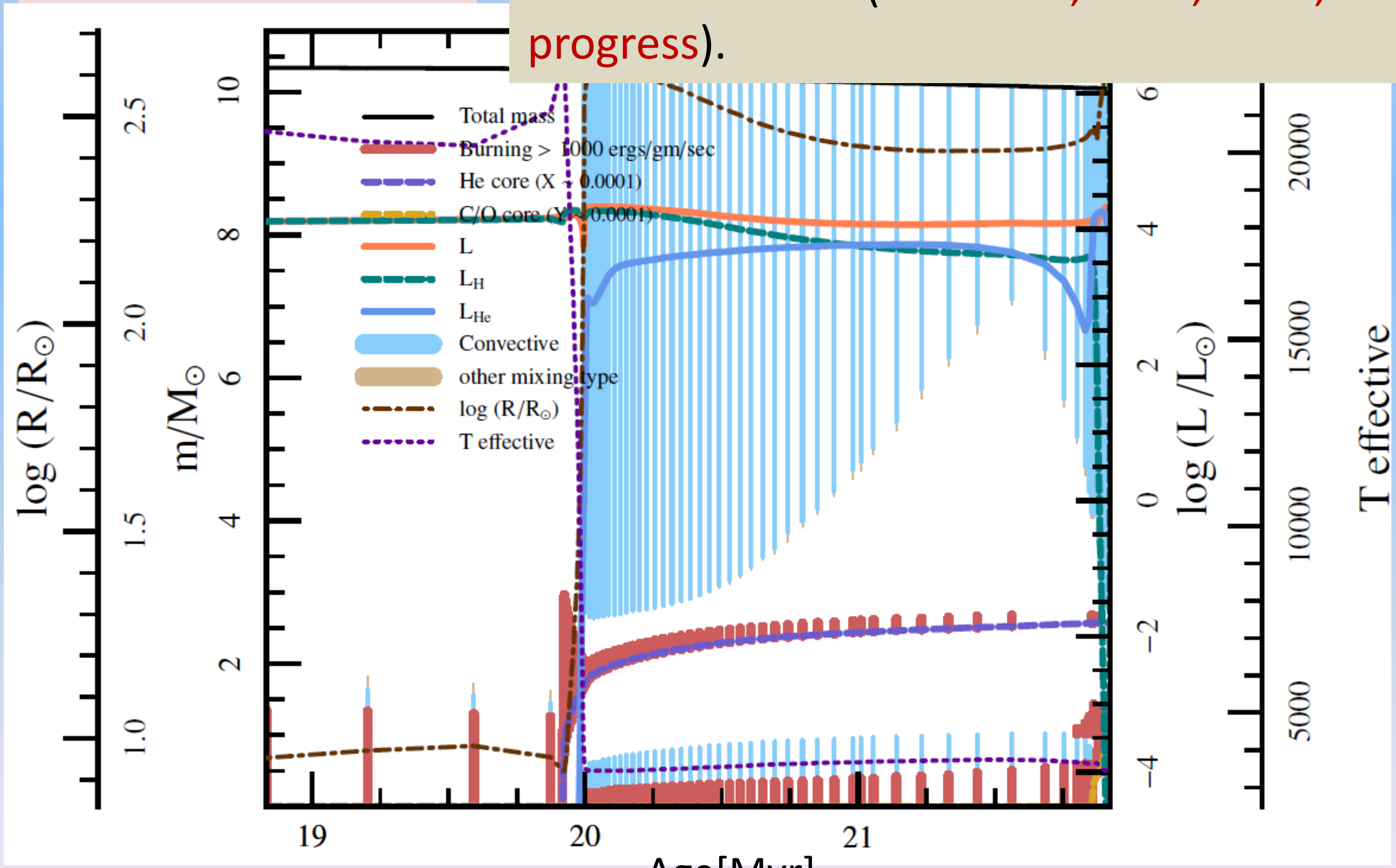


MESA Simulation. Friedland, Giannotti, Wise, **Phys. Rev. Lett. 110, 061101 (2013)**

Even Stronger Bounds?

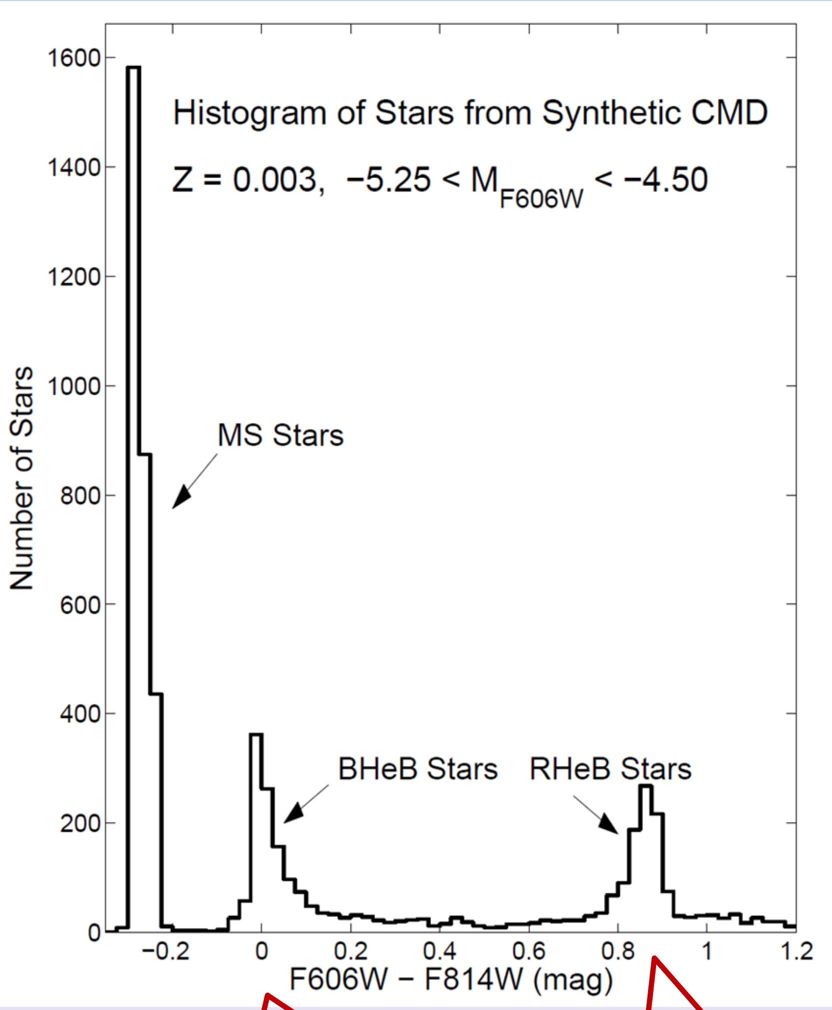
Other stars showed an even stronger response to axion cooling. However, these stars are somewhat harder to model (Friedland, M.G., Wise, work in progress).

$10.5 M_\odot$ star, g_{10}=0.6



Age[Myr]

Even Stronger Bounds?



Log T[k]=4

Log T[k]=3.7

In addition, the requirement that we used to derive the g_{10}=0.8 bound is <u>conservative</u>.

Given accurate counts, it may be possible to check whether the number of stars in the blue loop phase is reduced.

For example, g_{10} = 0.6 would reduce the time a 9.5 $M_\odot$ star spends on the blue loop by a factor of two or so. To get the same sensitivity for g_{10} from solar-mass stars requires knowing the numbers of HB stars to a 10% precision.

Conclusions and future directions

- Axions affect considerably the evolution of low and intermediate mass stars during the core He-burning stage.

- A value of g_{10}=1 (m_a<30 keV or so) would reduce the number of HB stars vs. RG stars by about 30%, in contradiction with observations.

- A value of g_{10}=0.8 (m_a<40 keV or so) would be sufficient to eliminate completely the blue loop phase of the stellar evolution for masses above 8 $M_\odot$. This would contradict observational data. In particular, it would contradict the observation of Cepheid stars in a broad range of pulsation periods.

- The massive star bound is conservative. A more stringent bound could be derived from a more a detailed analysis of the number of blue stars or a better modeling of stars in certain mass range.

Thank

You